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ANALYSIS OF GROUND HAZARDS DUE TO AIRCRAFTS AND MISSILES

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ABSTRACT

This generic study develops and applies a generalized methodology that approximates both the best estimate and pessimistic probabilities that an aircraft or a missile will impact a defined target area of an industrial, commercial, or residential facility. To best demonstrate the application of this methodology, the probability of impact for a hypothetical workplace facility is estimated.

INTRODUCTION

The potential risk to a worker may not be limited to the inherent risk associated directly with his employment. External risks may also be of concern.

One such external risk is the crashing of an aircraft into the industrial site. Such a crash and the associated fire could injure and kill many people.

This paper provides a generic approach to estimating the probability that an industrial site of specific dimensions and location will be struck by an aircraft.

This effort builds upon prior work that estimates the risk to ground population and structures from aircraft crashes (see Refs. 1–6).

The database upon which this analysis depends is drawn from statistics on hundreds of aircraft accidents and near accidents (see Refs. 7–9).

This generic methodology might be helpful to those charged with siting industrial complexes and facilities near airports and near airline flight paths.

Coordinates of a proposed facility are parametrically selected relative to fixed, assumed locations of (a) Victor airways, (b) general aviation airports, (c) air carrier airports, (d) military installations, and (e) other areas of air activity, such as crop dusting fields. The probability that an aircraft or missile will impact the target area is the sum of the individual probabilities that an aircraft or a missile originating from a particular source will impact the target area. The probability of target area impact and the magnitude of damage after impact depend on (a) purpose or category of flight, (b) mode of flight, (c) effective target area, (d) relative location of facility target area and air activity, (e) number of operations, (f) mode of impact, (g) pilot experience, (h) weather conditions, (i) time of day, (j) air traffic density, and so on. Here, we will discuss how to estimate the influence that each of these parameters has on the value of the impact probability. Site data and target area characteristics assumed for this study are discussed below. However, actual crash rates per mile are used (Refs. 7–9).

PURPOSE OR CATEGORY OF FLIGHT

Accident rate is a strong function of flight category (e.g., general aviation or pleasure flight, supplemental air carrier). Table 1 lists the aircraft accident rate per million miles flown as a function of flight category. The table is generated from U.S. aircraft crash statistics. Limited information on flight crash probability per missile category is also available.

Table 1

AIRCRAFT ACCIDENT RATES (PER 10^6 MILES FLOWN)
AS A FUNCTION OF THE JTH FLIGHT CATEGORY[a]

Flight Category	All Accidents	Major Accidents	Fatal Accidents
U.S. Certified Route & Supplemental Air Carriers (Air Miles Flown = 2.56×10^9)	0.023	0.011	0.004
U.S. General Aviation (Air Miles Flown = 3.48×10^9)	1.46	0.530	0.187
Military (Noncombat Missions)[b]	0.115	0.055	0.020

[a]Based on U.S. crash statistics. Local crash statistics have been examined but not used because of the relatively small number of aircraft crashes in the local regions (i.e., the limited number of local crashes do not provide a sufficient data base).
[b]Data not available as of start of this study Postulated to be equal to five times the U.S. Air Carrier rate.

The aircraft accident rates are listed as Class A (all accidents), Class B (major accidents), and Class C (fatal accidents) for years 1967 through 1984 or 1985 inclusive. In general, and except for the last couple of years, the aircraft accident rate has decreased since 1967. As a conservative prediction of future accident rates, the mean value of accident rates from 1967 through 1984 (or 1985) is used.

MODE OF AIRCRAFT FLIGHT

Table 2 compares the Class B (major accidents) aircraft accident rate (average for 1967 to 1984 or 1985) for each flight category as a function of the takeoff, inflight, and landing mode of operation. On an accident-per-mile basis, the safest mode of flight is the inflight mode. In this study, we assume that the takeoff mode encompasses the five miles after takeoff and the landing mode encompasses the five miles before touchdown. The inflight mode (including climb, inflight, and descent) is defined as the remaining air portion of the operation.

EFFECTIVE TARGET AREA

The effective target area is the sum of the base area of the building (with horizontal dimensions modified to include aircraft width), the shadow area (closely correlated to the vertical angle of approach and building height), and the aircraft skid area (in front of the facility).

Table 2

AIRCRAFT ACCIDENT RATES (PER 10^6 MILES FLOWN) AS A FUNCTION OF BOTH THE JTH FLIGHT CATEGORY AND THE KTH MODE OF OPERATION—MAJOR ACCIDENTS

Flight Category	Static	Taxi	Takeoff	Cimb	Inflight	Descent	Landing	Average
U.S. Certified Route & Supplemental Air Carriers	—	—	0.116		0.00519		0.450	0.011
U.S. General Aviation	—	—	2.44		0.318		2.44	0.530
U.S. Military (Noncombat Missions)	—	—	0.580		0.0260		2.25	0.055

TRUE TARGET AREA

The true target area is the total amount of land occupied by the plant (i.e., it is the base area of the target). For example, a cylindrical building of radius r (postulated to have been impacted by an aircraft of point dimension) has a true target area of A_p where (Ref. 1):

$$A_p = \pi r^2$$

SHADOW AREA

The shadow area depends on both the building height and the assumed angle of aircraft approach L (L is the angle that the aircraft makes with the horizon at the postulated impact point). This shadow area (not including the true target area) is the area obtained by a cylindrical projection following the angle L. In other words, it is the shadow cast by the building as a result of a projected angle of L. The sum of the true target area, A_p, and the shadow area, A_s, is defined, for the purpose of this study, as the virtual surface (or virtual area) of the target (Ref. 1):

$$A_v = A_s + A_p$$

For a cylindrical building of diameter D = 2r and height H, and fixed value of x with an upper hemispherical dome, the building virtual area is approximated (Ref. 1):

$$A_v^1 = \pi \frac{D^2}{4} \left\{\frac{3+\sqrt{2}}{4}\right\} + \frac{D}{2} \left\{H - \frac{D}{2}\right\}$$

In the equation, virtual surface determination is estimated, assuming that the aircraft is a physical point. Aircraft dimensions are not negligible with respect to building dimensions. Building dimensions can be artificially increased to account for aircraft dimensions by adding a distance d (where d equals one-half of aircraft wingspan) to the building dimensions. The cylindrical building virtual surface is then increased to:

$$A_v = \pi \left\{\frac{(D+d)^2}{4}\right\} \left\{\frac{3+\sqrt{2}}{4}\right\} + \left\{\frac{D+d}{2}\right\} \left\{H - \frac{D+d}{2}\right\}$$

Since skid area is generally considerably larger than virtual area (especially for faster aircraft), the total effective target area is much more sensitive to skid distance than it is to angle of impact. The value of L is usually less than 30°.

There is a similar analysis for noncylindrical buildings. For a rectangular building whose base dimensions are a and b and whose height is z, for $L > 0°$ virtual area of the building is (Ref. 1):

$$\overline{A}_v = \frac{(az)}{\tan £} + ab$$

for an aircraft traveling parallel to the side of the building whose dimension is b. For an aircraft traveling in an arbitrary direction, for $L > 0°$ the maximum virtual area is

$$A_v\,(\max) = z \left[\frac{(a^2+b^2)^{1/2} + 2d}{\tan £}\right] + a(b+2d)$$

where $(a^2 + b^2)^{1/2}$ is equal to the maximum building diameter seen by the approaching aircraft and where $b < a$ and $b + 2d > a$.

The total virtual area for juxtapositioned facilities is less than the sum of the virtual areas for each facility unit because of the mutual shadowing effect of each facility (i.e., an aircraft would be less likely to impact a unit that was shadowed or shielded by another unit immediately in front of it).

SKID AREA

If an aircraft were postulated to impact the land immediately in front of a structure, we might expect that the aircraft would skid into that structure. Depending on terrain and aircraft weight, size, and its horizontal component of velocity, the aircraft can skid up to approximately one mile (for a high velocity military aircraft, the skid length is typically 0.6 miles. For a U.S. air carrier the typical skid length may be 0.3 miles, and for a U.S. general aviation the skid length is typically 0.06 miles (Ref. 1).

Insight into the phenomenon of skidding may be gained by considering the motion of an aircraft on the ground as the linear motion of a body with an initial velocity V_o (mph) and a uniform deceleration equal to a multiple K of gravity. The simplest model leads to a skid distance of:

$$X_m = (6.3 \times 10^{-6}) \left[\frac{V_o^2}{K}\right] \text{miles}$$

The value of K is directly proportional to the amount of friction between the skidding aircraft and the terrain. Typical values of K may be estimated to vary between 2.5 and 5.

The skid area, A_m, is defined as the product of the sum of the widths of the impacting aircraft and the building postulated to be impacted and the skid distance, then:

$$A_m = (2d + D)\,(X_m)$$

TOTAL TARGET AREA

The total effective target area, A_E, is the sum of the true target area, shadow area, and skid area:

$$A_E = A_p + A_s + A_m$$

To arrive at numerical results, we assume that the total target area of the proposed facility is 0.2 mi^2.

RELATIVE LOCATION OF FACILITY TARGET AREA AND AIR ACTIVITY

Figure 1 illustrates a hypothetical region divided into a matrix of ten by ten equal-sized subregions. The region contains four general aviation airfields (in subregions x = 2, y = 7; x = 3, y = 2; x = 4, y = 2; and x = 4, y=7), three air carrier airfields (at x = 2, y = 5; x = 3, y = 8; and x = 10, y = 10), one military air base (at x = 8, y = 4), one military missile base (at x = 9, y = 4), one crop dusted subregion (at x = 10, y = 8), and an airway (from x = 6, y = 10 to x = 10, y = 5).

NUMBER OF AIRCRAFT OPERATING

Table 3 lists the air activity that has been assumed for each of the hypothetical air facilities identified in Fig. 1.

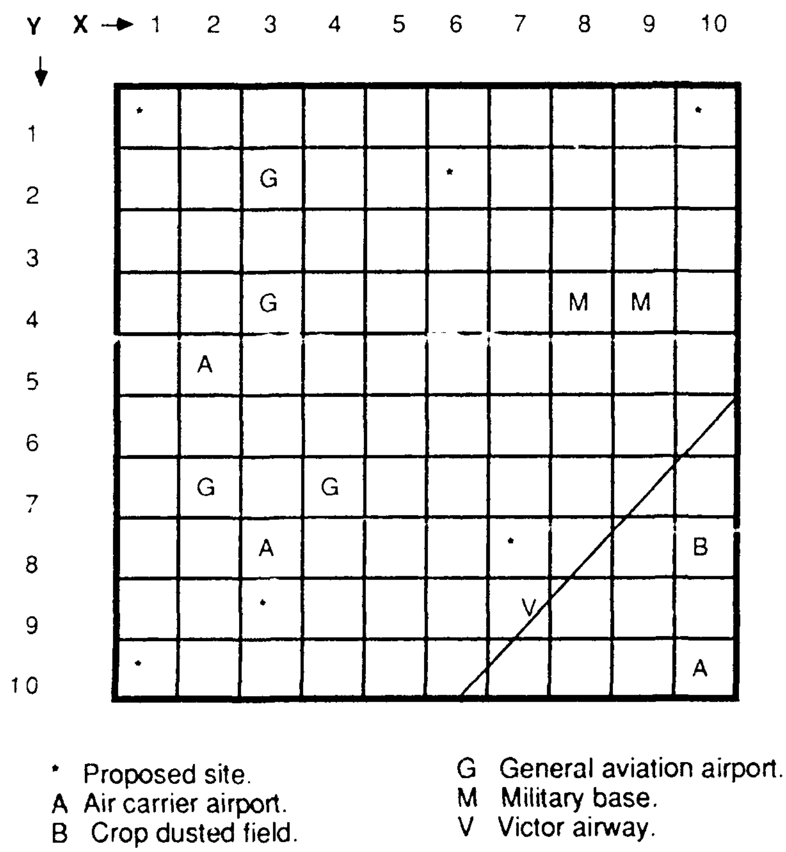

Fig. 1 - Relative location of proposed site and air activity

Table 3

AIR ACTIVITY IN HYPOTHETICAL REGION

Assumed Subregion	Assumed Locations	Number of Assumed Operations per Year	Comments
x = 2	y = 5	100,000	Assume all aircraft are fixed wing, two or more engine commercial aircraft
x = 2	y = 7	20,000	Assume all aircraft are single engine, fixed wing aircraft
x = 3	y = 2	25,000	Assume all aircraft are single engine, fixed wing aircraft
x = 3	y = 4	15,000	Assume all aircraft are single engine, fixed wing aircraft
x = 3	y = 8	50,000	Assume all aircraft are fixed wing, two or more engine commercial aircraft
x = 4	y = 7	25,000	Assume all aircraft are single engine, fixed wing aircraft
x = 6 to x = 10	y = 10 to y = 5	100,000	Assume one-third of aircraft are U.S. air carrier and two-thirds are U.S. general aviation
x = 8	y = 4	5,000	Assume single engine jet aircraft
x = 9	y = 4	100	Assume medium-size surface to air missile
x = 10	y = 8	100	Assume all aircraft are single engine, fixed wing aircraft
x = 10	y = 10	50,000	Assume all aircraft are fixed wing, two or more engine commercial aircraft

OTHER FACTORS AFFECTING AIRCRAFT CRASH PROBABILITY

The flight category and the flight mode are the factors that most affect air crash probabilities (Refs. 7, 8). All pilots (U.S. air carrier, U.S. general aviation, and U.S. military) must meet a minimum standard of performance. An increase in a particular pilot's experience over this minimum standard (provided he remains within the same flight category) will not significantly affect his ability to fly safely. Weather conditions and time of day do, to some degree, affect aircraft safety (Ref. 8). However, these two factors do not affect safety as significantly as flight category or flight mode. The effect of air traffic density on air crash probability is most influential near airports and is quantitatively considered when estimating the aircraft accident rate during the landing and takeoff modes of flight. Aircraft accident rate cannot be linked strongly to aircraft type. (For example, even though the accident rate is different for a DC-10 and a Boeing 707 aircraft, these differences are due more to statistical variances rather than to one aircraft being safer than the other.)

FORMULATION OF AIRCRAFT CRASH PROBABILITY PER EFFECTIVE TARGET AREA

In this section we formulate the aircraft crash probability per effective area using a best estimate or (Cornell) and conservative (or straight line) approach. The best estimate model uses a Gaussian-shaped probability distribution to estimate the postulate aircraft impact location orthonormal to the intended flight path at the point at which difficulty originated. The conservative approach model uses a straight line probability distribution.

BEST ESTIMATE MODEL

In the special case of the straight path, the probability that an aircraft will impact a particular point diminishes with the projected (orthonormal) distance (x_p) from the location on the path at which the trouble began (see Fig. 2).

For any impact distribution, F(x), the probability that a given impact is in a strip of width Δh, located at a distance x_p, and parallel to the intended flight path is $\Delta h \times F(x_p)$. Postulating that there is such a hit (and assuming that the intended path is straight, a sufficient distance either side of the plant), there is no information provided about the longitudinal location of the hit or the point of origin of the accident. Therefore, the event that the postulated impact point lies in any perpendicular strip of width ΔL (see Fig. 2) is probabilistically independent of the event that the point lies in the Δh strip. As a consequence, the probability of the joint occurrence of the two events along flight path i is the product of their probabilities or $[\Delta h] \times F(x_p) \times [P \times \Delta L]$ where P is the crash probability per mile.

For an aircraft in the jth category of flight and in the kth mode of operation, the impact distribution function of $F_{j,k}(x)$ and the crash probability per mile is $P_{j,k}$.

The total probability per year that any aircraft in any of the i flight paths, in any of the j flight categories, and in any of the k modes of operation will impact the target area is defined in Table 4.

For $F_{j,k}(x)$ there are, unfortunately, almost no data, because it is very difficult to establish the exact location and distance away of the plane when the trouble leading to the crash originated. The function $F_{j,k}(x)$ is anticipated to be symmetrical and to decay

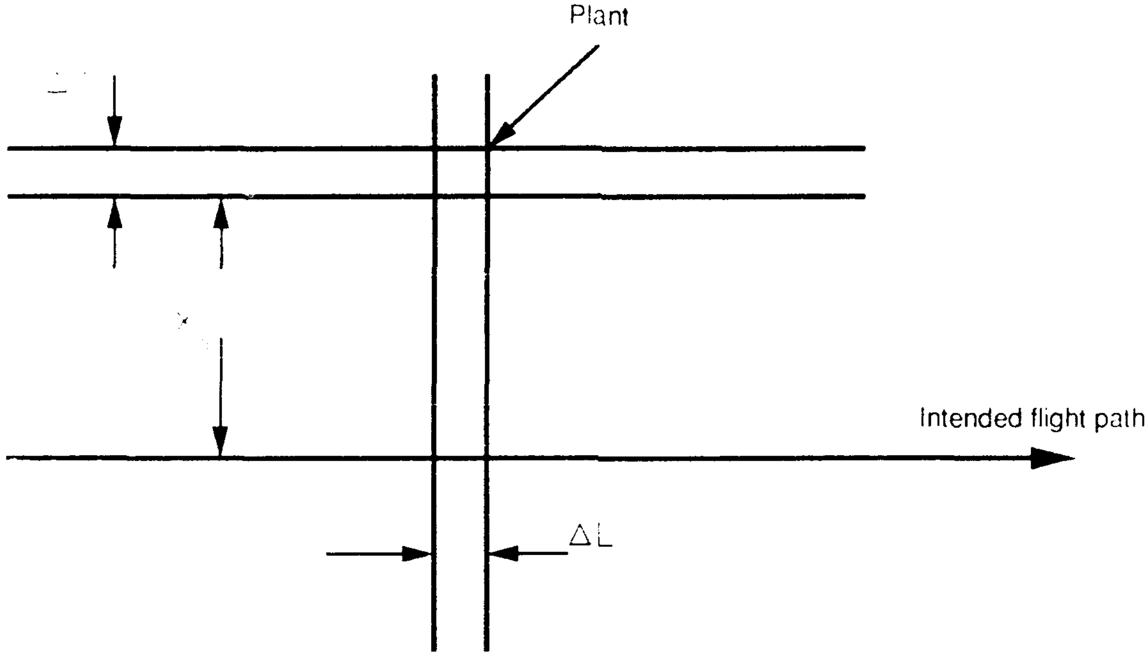

Fig. 2 - Straight line flight path near an industrial complex in the vicinity of Phoenix, Arizona

away from the location on the intended flight path where the trouble first began. The simplest such distribution, and the one recommended by information theory concepts, is the exponential distribution:

$$F_{j,k}(x) = 1/2\ \gamma \exp(-\gamma |x|) \quad -\infty < x < \infty$$

The mean of the absolute value of x is $1/\gamma$. Based on investigations of many aircraft accidents and on previous studies, the best subjective estimate of γ is:

$\gamma_j = 8 \quad = \quad 1\ \text{mile}^{-1}$ (military aircraft) (Ref. 9)

$\gamma_j = 3,4,5,7 \quad = \quad 2\ \text{mile}^{-1}$ (U.S. general aviation other than aerial application) (Refs. 7–8)

$\gamma_j = 6 \quad = \quad 1\ \text{mile}^{-1}$ (U.S. general aviation, aerial application only) (Refs. 7–8)

$\gamma_j = 1,2 \quad = \quad 1.6\ \text{mile}^{-1}$ (U.S. air carrier) (Refs. 7–8)

STRAIGHT LINE MODEL (CONSERVATIVE APPROACH)

In the straight line model, it is assumed that $F_{(j,k)} = 1/W_{(j,k)}$ = constant, where $W_{(j,k)}$ is the width of the particular flight path (plus twice the distance from the airway edge to the site when the site is outside of the airway), for aircraft type j in its kth mode of flight. For x greater than about a mile, the straight line model is more conservative than the best estimate model.

OTHER TYPICAL EQUATIONS

A few typical equations that can be used to estimate crash probability . listed in Table 4. Other equations have been developed.

TYPICAL RESULTS

Typical results are shown in the abridged Table 5. An optimal site (in terms of minimizing the probability of external hazards from postulated aircraft and missile strikes) can be located within a selected region of prespecified air activity. Examination of Table 5 indicates that although site location at x = 7, y = 8 produces the smallest estimated total crash probability, site locations at x = 3, y = 9 and x = 10, y = 1 may be far more attractive, since these latter sites have considerably fewer large aircraft contributing to the probability estimate. If pessimistic rather than best estimate techniques and data were used to generate Table 5, then the estimated probabilities would be about one order of magnitude larger.

Other proposed industrial sites within the region can be selected to locate the minimum risk subregion.

Table 4

TYPICAL EQUATIONS USED TO APPROXIMATE BEST ESTIMATE AND PESSIMISTIC IMPACT PROBABILITIES

Air Activity	Probability of Impact: Best Estimate Technique	Probability of Impact: Pessimistic Technique
Victor Airways	$\sum_i \sum_j \sum_k \left\{ N_{(i,j,k)} \times A_{(i,j,k)} \times F_{(j,k)} \times C_{(j,k)} \right\}^{(1)}$	$\sum_i \sum_j \sum_k \left\{ \frac{N_{(i,j,k)} \times A_{(i,j,k)} \times C_{(j,k)}}{W_{(i,j)}} \right\}^{(2)}$
Airports within 5 miles	$\sum_i \sum_j \sum_k \left\{ N_{(i,j,k)} \times A_{(i,j,k)} \times C_{(j,k)} \times P_o \times P_r \right\}^{(3,4)}$	$\sum_i \sum_j \sum_k \left\{ \frac{N_{(i,j,k)} \times A_{(i,j,k)} \times C_{(j,k)}}{W_{(i,j)}} \right\}$ where j = takeoff or landing (pessimistic if 0 >10°)
Missile base > 5 miles away	$\sum_i \left\{ \frac{A_{(j)}}{\pi r^2} N_{(j)} \times P_{(j)} \times P'_{(j)} \times P'' \right\}$	$\sum_i \left\{ \frac{A_{(j)}}{\pi r^2} N_{(j)} \times P_{(j)} \times P'_{(j)} \right\}$ (pessimistic if missiles are not launched in general direction of site)

Legend

$A_{(i,j,k)}$	=	Effective target area in square miles (1)
$C_{(j,k)}$	=	Probability per mile that an aircraft or missile will crash (1)
$F_{(j,k)}$	=	Distribution of impacts orthonormal to the intended flight path (1)
$N_{(i,j,k)}$	=	Number of operations per year
$P_{(j)}$	=	Ratio of the number of missiles that are destined to crash to total number launched
$P'_{(j)}$	=	Probability that a missile, which is destined to crash, will not be successfully aborted
$P''_{(j)}$	=	Ratio of probability that a missile will be launched in the direction of the site to the probability that it will be launched in average direction
P_o	=	Normalization factor that relates air crash probability within 5 miles of an airport to the angle from the intended flight path (3,4)
P_r	=	Normalization factor that relates aircraft probability within 5 miles of an airport to the distance from the runway (3,4)
r	=	Distance from airport or missile base to site
W	=	Width of airway (plus twice the distance from the airway edge to the site when the site is outside of the airway) in miles (2)
Subscripts		
i	=	Flight path identification (e.g., Victor Airway V-97)
j	=	Aircraft or missile site or type (e.g., U.S. General Aviation—Pleasure Type
k	=	Mode of flight (viz., takeoff, inflight, landing)

Table 5

PROBABILITY THAT AIRCRAFT WILL IMPACT INDUSTRIAL SITE
AS A FUNCTION OF SITE LOCATION

Site Coordinates X	Site Coordinates Y	Probability of Target Area Impact (per Year[a])	Percentage of Probability Due to Aircraft Type
1	1	5.2×10^{-7}	90% due to general aviation, 3% due to military aircraft, 2% due to missiles, and 5% due to air carrier.
1	10	8.4×10^{-8}	85% due to general aviation, 1% due to military aircraft, 1% due to missiles, and 13% due to air carrier.
6	2	1.3×10^{-7}	90% due to general aviation, 4% due to military aircraft, 3% due to missiles, and 3% due to air carrier.
3	9	4.1×10^{-8}	70% due to general aviation, 2% due to military aircraft, 2% due to missiles, and 26% due to air carrier.
7	8	2.1×10^{-8}	50% due to general aviation, 3% due to military aircraft, 2% due to missiles, and 45% due to air carrier.
10	1	6.6×10^{-8}	85% due to general aviation, 5% due to military aircraft, 3% due to missiles, and 7% due to air carrier.

[a]Using best estimate technique.

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